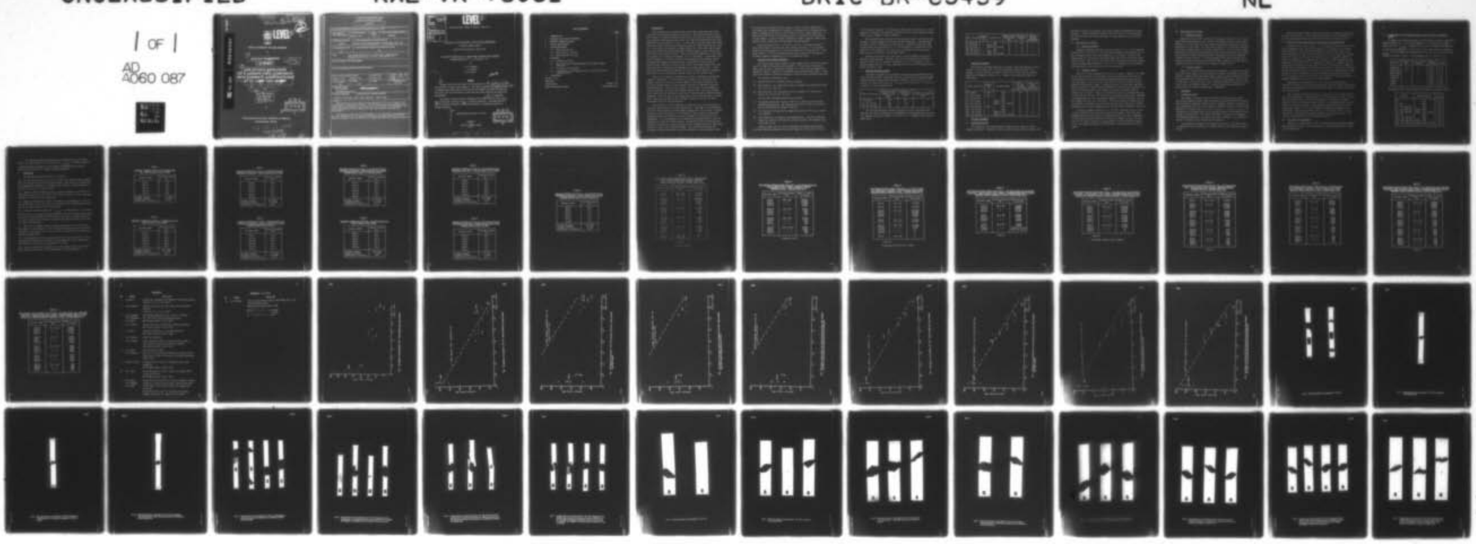
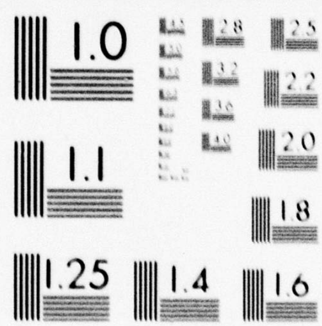
AD-A060 087 ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 11/5
THE FATIGUE BEHAVIOUR OF A CARBON FIBRE COMPOSITE WITH LAMINATE--ETC(U)
MAR 78 J B STURGEON, F S RHODES, B B MOORE
UNCLASSIFIED RAE-TR-78031 DRIC-BR-63439 NL

1 OF 1
AD
A060 087



END
DATE
FILMED
12-78
DDC



MICROCOPY RESOLUTION TEST CHART

TR 78031

AD A060087

(18) DRIC (19) BR634397

(14) RAE-TR-78031

UNLIMITED

LEVEL II

5c

ROYAL AIRCRAFT ESTABLISHMENT

*

(9) Technical Report 78031 (12) 54p.

(11) Mar[redacted]78

(6)

THE FATIGUE BEHAVIOUR OF A CARBON FIBRE COMPOSITE WITH LAMINATE CONSTRUCTIONS OF 0°, 0[redacted]° AND 90[redacted]°.

deg

+ or - 45 deg

by

(10) J.B. Sturgeon, F.S. Rhodes, B.B. Moore

*

Procurement Executive, Ministry of Defence
Farnborough, Hants

78 10 17 077

UNLIMITED

310 450

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TR 78031	N/A	UNLIMITED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
850100	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title: The fatigue behaviour of a carbon fibre composite with laminate constructions of 0^o, 0 ± 45^o and 90 ± 45^o

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Sturgeon, J.B.	Rhodes, F.S.	Moore, B.B.	March 1978	52	12

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.
N/A	N/A		Mat 343

15. Distribution statement

(a) Controlled by – [redacted]

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Fatigue. Multiplied carbon fibre composite. Epoxy resin.

17. Abstract

Fatigue tests have been made on plain specimens of 0^o, 0 ± 45^o and 90 ± 45^o orientations of carbon fibre composite. The effect of holes and preconditioning by thermal ageing and humidity were studied with 0 ± 45^o and 90 ± 45^o laminates. S-N curves were obtained from all these tests and some fractured specimens were photographed.

The results provide further confirmation that 0 ± 45^o CFC is notch sensitive to monotonic loadings but not to fatigue conditions. Prolonged ageing at 40^oC and humidity exposure at 40^oC and 95% RH had no significant effect on fatigure endurance.

F5910/1

LEVEL II

UDC 661.66-426 : 678.6 : 678-419 : 620.178.3

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 78031 ✓

Received for printing 14 March 1978

THE FATIGUE BEHAVIOUR OF A CARBON FIBRE COMPOSITE WITH LAMINATE CONSTRUCTIONS OF 0^{o}, 0 ± 45^{o} AND 90 ± 45^{o}

by

J. B. Sturgeon

F. S. Rhodes

B. B. Moore

DEGREE

SUMMARY

Fatigue tests have been made on plain specimens of 0^{o}, 0 ± 45^{o} and 90 ± 45^{o} orientations of carbon fibre composite. The effect of holes and preconditioning by thermal ageing and humidity were studied with 0 ± 45^{o} and 90 ± 45^{o} laminates. S-N curves were obtained from all these tests and some fractured specimens were photographed.

+ OR −

+ OR − DEGREE

The results provide further confirmation that 0 ± 45^{o} CFC is notch sensitive to monotonic loadings but not to fatigue conditions. Prolonged ageing at $40^{o}C$ and humidity exposure at $40^{o}C$ and 95% RH had no significant effect on fatigue endurance.

Departmental Reference: Mat 343

78 10 17 077

LIST OF CONTENTS

1 INTRODUCTION

Early fatigue tests on unidirectional carbon fibre composites (CFC) indicated that the fatigue performance was superior to many other materials, particularly metals, but unlike many metals where failure is relatively slow and statistically predictable CFC failures were found to be rapid and unpredictable with lives extending over many decades of cycles. In some cases, especially when high modulus fibres were used, failure often occurred only when the fatigue stresses were close to, or even within, the montonic strength scatter band. With other lower modulus fibres the stress level below which almost infinite fatigue lives occur was also quite high in zero-tension fatigue[1]. Whilst the absolute magnitude of this stress level depends on the composite strength, if it is expressed as a percentage of the tensile strength it is found to decrease with decreasing fibre modulus. Recent tests made with composite containing type 3, low modulus, fibres indicate a greater fatigue sensitivity with much less scatter than higher modulus fibre composites and more conventional S-N diagrams can be drawn from the data. It was found that multi-directional composite also suffers fatigue damage, by cracking, quite early in the testing whilst complete rupture occurs very much later[2].

There are two important considerations to bear in mind when investigating fatigue of composites:- (i) which aspects of fatigue are a function of the laminate construction and are therefore common to all similar composites, and (ii) which characteristics of any particular fibre/resin combination influence fatigue behaviour? Under the first heading lies the study of gross damage and failure mechanisms for similar CFC laminate constructions. The second heading covers aspects such as the differences between fibres and matrices which determine endurances before the onset of any single type of failure and the extent to which matrix resin type and fibre surface treatment influence the effect of other environment factors on fatigue behaviour.

The influence of fibre orientation is relatively easy to study and this is the major consideration of the work reported here. Some aspects of preconditioning in the form of ageing and environmental exposure were also studied. To extend the work to study the influence of the fibres and resin requires an evaluation technique which not only detects the onset of damage but can also monitor its propagation. It is advantageous if the technique is non-destructive so that the specimen can be used for further testing. Unfortunately when this work was performed no non-destructive testing facilities were available which were sufficiently sensitive to detect fine cracks and damage. Also insufficient material was available to mount an extensive destructive evaluation in which specimens could

be sectioned and polished to reveal fatigue cracking. Another complication is that simple visual examination of specimens is unreliable for assessing onset and growth of damage and the opacity of CFC prevents all but surface inspection. In multi-directional CFC the outer surface may give no indication of the condition of inner layers. In spite of these limitations a number of general aspects were observed during fatigue and failed specimens were photographed.

Tests were made on 0^o, 0 ± 45^o and 90 ± 45^o CFC. The unidirectional 0^o material was tested to indicate the basic material endurance, 0 ± 45^o was more extensively tested because it is a practical material for structural use. A composite with 90 ± 45^o fibre orientations gives some indication of resistance to secondary loadings consequently it too was extensively tested.

2 MATERIALS AND TESTING TECHNIQUES

The carbon fibres were low modulus, high strength, type 3 which were surface treated to improve interlaminar shear strength. The resin was a proprietary epoxy, Code 69, made by Fothergill and Harvey Ltd. This firm also supplied pre-impregnated sheets of material to the MOD(PE) specification NM 547 issue 3. These sheets were assembled at RAE and laminated in the Structures Department autoclave.

The laminate constructions were:

(1) Unidirectional 0^o, containing 8 plies of prepreg.

(2) Multi-plied 0 ± 45^o, containing 6 plies of prepreg, the construction being; +45, -45, 0, 0, -45, +45.

(3) Multi-plied 90 ± 45^o, containing 6 plies of prepreg, the construction being; +45, -45, 90, 90, -45, +45.

The autoclave laminating schedule was as follows;

(1) The prepreg sheets were raised to 130^oC over a period of 2¼ hours with maximum vacuum applied. The temperature was held at 130^oC for 20 minutes before pressurizing the chamber to 690 kPa.

(2) The vacuum was released and the temperature raised to 175^oC over a period of 45 minutes.

(3) Both temperature and pressure were maintained for 1 hour after which the chamber was cooled to 60^oC and the pressure released. The laminates were then ready for use.

Specimen blanks were cut from the laminates with diamond tipped wheels. The nominal specimen dimensions were 240 mm length and 20 mm width for 0^o and

0 ± 45^o material whilst 90 ± 45^o blanks were 250 mm long and 40 mm wide. All the eight-ply test-pieces were nominally 2 mm thick and the six-ply specimens, being thinner, were a nominal 1.5 mm in thickness.

Thin aluminium alloy end plates 40 mm long were bonded to the ends of each specimen to prevent damage in the fatigue machine wedge grips. Some specimens contained a stress concentration in the form of a centrally drilled hole which occupied 10% of the specimen width. In 0 ± 45^o material the diameter was 2 mm and in 90 ± 45^o composite it was 4 mm. All calculations of stress have been based on the nett section at the specimen centre.

Monotonic and fatigue tests were made in a Mayes' ESH100D electroservo-hydraulic fatigue machine. Monotonic tests were performed with the machine in position control and an actuator displacement rate of 2.5 mm/minute. Zero-tension fatigue tests ($P \pm P$) were conducted at 10 Hz on 90 ± 45^o material and at 20 Hz on 0^o and 0 ± 45^o.

3 MONOTONIC STRENGTH RESULTS

The tensile strength of each laminate construction was determined by slow speed monotonic testing. Individual results of plain material without preconditioning or stress concentration are given in Tables 1, 2 and 6 for 0^o, 0 ± 45^o and 90 ± 45^o materials respectively. The means and coefficients of variation on strengths for these laminates were:

Fibre orientation	Tensile strength measured in the 0^o direction MPa	Coefficient of variation on strength %	Number of the table containing detailed data
0^o (8 ply)	1158	10.7	1
0 ± 45^o (6 ply)	646	3.6	2
90 ± 45^o (6 ply)	188	3.9	6

All the other monotonic specimens contained a stress concentrator and some were also aged or subjected to environmental preconditioning prior to testing. Details are given in Tables 3 to 5 and 7 to 9. A resumé of the results is given below:

Fibre orientation	Diameter of hole mm	Preconditioning	Tensile strength measured in the 0^{o} direction MPa	Coefficient of variation on strength %	Number of the table containing detailed data
0 ± 45^{o} (6 ply)	2	None	412	10.0	3
0 ± 45^{o} (6 ply)	2	3000 h, 40^{o}C	417	5.7	4
0 ± 45^{o} (6 ply)	2	3000 h, 40^{o}C, 95% RH	418	7.5	5
90 ± 45^{o} (6 ply)	4	None	181	4.2	7
90 ± 45^{o} (6 ply)	4	3000 h, 40^{o}C	178	3.7	8
90 ± 45^{o} (6 ply)	4	3000 h, 40^{o}C, 95% RH	175	4.6	9

4 FATIGUE TEST RESULTS

Each group of specimens mentioned in section 3 above was subjected to zero-tension (P ± P) fatigue tests. Failure was defined as total rupture of the specimen. Detailed results are given in Tables 10 to 18 and they are also presented as S-N diagrams in Figs 1 to 9. A guide to the tables and figures is given below:

Fibre orientation	Diameter of hole mm	Preconditioning	Number of the table containing detailed data	Number of figure showing the S-N curve
0^{o} (8 ply)	None	None	10	1
0 ± 45^{o} (6 ply)	None	None	11	2
0 ± 45^{o} (6 ply)	2	None	12	3
0 ± 45^{o} (6 ply)	2	3000 h, 40^{o}C	13	4
0 ± 45^{o} (6 ply)	2	3000 h, 40^{o}C, 95% RH	14	5
90 ± 45^{o} (6 ply)	None	None	15	6
90 ± 45^{o} (6 ply)	4	None	16	7
90 ± 45^{o} (6 ply)	4	3000 h, 40^{o}C	17	8
90 ± 45^{o} (6 ply)	4	3000 h, 40^{o}C, 95% RH	18	9

5 FAILURE APPEARANCE

5.1 Unidirectional CFC

The failures of the unidirectional 0^{o} composite were similar to those reported previously[3]. Monotonic failures usually occurred within the body of the

specimen but rupture was energetic with almost complete disintegration of many specimens. Fatigue specimens frequently failed at or near to the end-plates and the failure was more localized without the disintegration of the monotonic specimens.

5.2 Multi-plied $0 \pm 45^{\circ}$ CFC

(a) Monotonic failures

Examples of monotonic failures are given in Figs 10 to 13. Plain material usually failed in the centre of the test piece although one specimen did fail at the end-plates, Fig 10, this latter behaviour is not common. In general the damage seems to be localized to the region where rupture occurred and the break is fairly clean. When a hole is introduced into the specimen the failure surface almost invariably passes through it, Figs 11 to 13. Preageing and environmental conditioning had little effect on the failure appearance.

(b) Fatigure failures

Figs 14 to 17 show specimens which failed in fatigue. Common to all groups was the fact that high cycle specimens (that is specimens which survived for long lifetimes) were all more extensively damaged than high stress, hence low cycle specimens. In fact for short lifetimes the failure was almost indistinguishable from monotonic breaks. Sometimes there was a little more cracking in fatigue specimens to identify them from monotonic test-pieces but separation of a mixture of broken specimens into fatigue and monotonic failures cannot be achieved with confidence. High cycle specimens can easily be distinguished and in plain material the outer 45° layers often delaminated and fell away. Specimens containing holes were not so extensively damaged as the plain material but were more damaged than low cycle test-pieces. The run-up failures in Figs 15 and 17 are examples of specimens that failed either on the first load cycle or almost immediately after testing commenced and at the most did not experience 100 cycles.

The mode of damage progression in $0 \pm 45^{\circ}$ CFC containing a hole has been outlined elsewhere[3] for another epoxy resin matrix system. The recent work supports the outline given there of cracking starting at the hole, spreading to the test-piece edge and laddering by reflection of damage from the $+45^{\circ}$ layer into the -45° layer leading to a zig-zag pattern of failure bands and rupture sites. No evidence was found in this work which conflicted with the earlier report.

5.3 Multi-plied 90 ± 45° CFC

(a) Monotonic failures

Monotonic failures of 90 ± 45° CFC are illustrated in Figs 18 to 21. Fig 18 shows failed plain specimens which indicate the combined failure of splitting or shearing of the 45° layers with some interply delamination coupled with a simple break across to 90° fibres. As illustrated in Figs 19 to 21 specimens containing holes did not always break at the stress concentration. In all cases the damage associated with failure was not extensive being confined around one small region. When failure was directly through the hole a straight tensile break sometimes occurred, see Figs 20 and 21. In plain specimens and in holed specimens where failure was remote from the hole the failure surface appears to contain more contributions from the 45° plies giving a sloping or jagged fracture.

(b) Fatigue failures

Figs 22 to 25 show typical fatigue failed specimens. A superficial examination would reveal almost no obvious differences between the fatigue and monotonic failures. However fatigue specimens usually contain interply delaminations caused by the zig-zag ladder cracking of the 45° layers[3] and splitting of the 90° layer in some cases. The general form of the cracking and damage progression was similar to other work reported elsewhere[3]. Preconditioning and preageing had no obvious effect on the failure mechanisms or appearance.

6 DISCUSSION

6.1 Variability of CFC

The summary of tensile strengths in section 3 above shows that multidirectional composites exhibit lower variability than unidirectional 0° material. This confirms the behaviour reported earlier[3] though it should be noted that the plain rectangular test-piece is not ideal for monotonic testing of unidirectional composite[4]. Drilling a hole in 0 ± 45° CFC seems to increase the variability of strength also confirming previous work though the effects of environment and preageing are contradictory. The earlier work showed an increase in variability with preconditioning whilst the latest work shows a decrease. Low variability for 90 ± 45° material also confirms previous results.

By comparison with metals, the variability of CFC is of the same order as or even better than cast metals but is higher than the very consistent wrought alloys[5].

0

Under zero-tension fatigue conditions the scatter in endurances was greater for plain 0° and plain $0 \pm 45^\circ$ orientations compared with earlier work[3] but for all the remaining specimen groups it was much the same as found previously.

6.2 Notch sensitivity under monotonic and fatigue loading conditions

A 2mm hole in the centre of the $0 \pm 45^\circ$ test-piece reduced the nett section tensile strength by 36%. On the other hand $90 \pm 45^\circ$ CFC appears to be almost notch insensitive, the reduction here being only a few percent. This is an interesting result for the notch sensitivity of $\pm 45^\circ$ CFC is slight[6] and cracking within 45° layers does not result in immediate loss of strength but merely an increase in compliance[7]. Unidirectional 0° material is almost completely notch insensitive[8]. Only when 0° and $\pm 45^\circ$ laminae are combined as a laminate does any significant notch sensitivity arise and it must be the interaction of damage in the 45° plies spreading into the 0° layers which leads to a reduction in strength. Because 0° plies carry most of the load in $0 \pm 45^\circ$ CFC any damage caused to them results in a loss of strength of the whole laminate whereas the 90° plies in $90 \pm 45^\circ$ CFC carry only $\frac{1}{3}$ of the load so this construction is less susceptible to damage propagating from the 45° plies into 90° laminae.

Substantial notch sensitivity in $0 \pm 45^\circ$ CFC is well established. A reduction in strength of 24% was found previously[3] and other workers using different fibre/resin systems have reported 35% and 40% losses in strength, see Refs 9 and 10 respectively.

Under fatigue conditions neither $0 \pm 45^\circ$ nor $90 \pm 45^\circ$ CFC showed significant notch sensitivity. Indeed provided $0 \pm 45^\circ$ specimens do not fail on run-up that is during the first 100 cycles) the endurance is similar to unnotched material. However all specimens which survive to long endurances develop cracks fairly early in their lifetimes. These propagate progressively[3] and to some extent they uncouple the 0° and 45° laminae thus making the composite notch insensitive. The hole was usually the site of fatigue damage initiation and the fracture surface generally passed through it but not in every case. The reasons for this have been fully discussed elsewhere[2,3].

6.3 The effect of environment

Exposure to a temperature of $40^\circ C$ for 3000 hours with and without humidity had no significant effect on either monotonic or fatigue behaviour when tested at room temperature.

6.4 A comparison of zero-tension fatigue in CFC with that in aluminium alloys

To compare the fatigue performance of CFC with that of metals a generalized fatigue-ultimate ratio $_aR_b$ has been suggested[3]. For zero-tension fatigue results the ratio $R_{0.0\ 10^6}$ is defined as the ratio of fatigue stress amplitude for 50% failure probability at 10^6 cycles to the tensile strength. Values of $R_{0.0\ 10^6}$ for some common thin aluminium alloys are given below. Data have been extracted from Refs 11 and 12. Holed specimens had K_T values of 2.7.

Material	Thickness mm	Source of data reference	Type of specimen	$R_{0.0\ 10^6}$
7050-T76	3.17	11	Plain	0.16
DTD 5070A	1.5	12	Plain	0.19
DTD 5070A	"	"	Holed	0.13
2024-T81	"	"	Plain	0.16
2024-T81	"	"	Holed	0.12
BSL73	"	"	Plain	0.15
BSL73	"	"	Holed	0.09

The same ratio for the CFC tested here yielded the following results.

Material	Preconditioning	$R_{0.0\ 10^6}$
0^o	None	0.34
0 ± 45^o	None	0.32
0 ± 45^o, 2mm hole	None	0.45
0 ± 45^o, 2mm hole	3000 h, 40^oC	0.45
0 ± 45^o, 2mm hole	3000 h, 40^oC, 95% RH	0.45
90 ± 45^o	None	0.26
90 ± 45^o, 4mm hole	None	0.26
90 ± 45^o, 4mm hole	3000 h, 40^oC	0.24
90 ± 45^o, 4mm hole	3000 h, 40^oC, 95% RH	0.26

If the specimens containing holes were of isotropic material the appropriate K_T value would be 2.7. The results for $R_{0.0\ 10^6}$ are almost identical to those presented previously[3] and once again they demonstrate the greater potential of CFC for use in fatigue loading environments.

7 CONCLUSIONS

The conclusions from this work are as follows:-

(a) The notch sensitivity of $0 \pm 45^\circ$ CFC can be severe under monotonic loading whilst in fatigue the sensitivity is much reduced. The reduction in sensitivity is accompanied by cracking of the composite which reduces the effectiveness of the hole in its role as a stress raiser.

(b) Ageing at 40°C for 3000 hours with or without a humidity of 95% RH has no significant effect on $0 \pm 45^\circ$ or $90 \pm 45^\circ$ CFC which contains a stress raiser when testing is carried out at room temperature.

(c) Though not discussed in detail in this Report, the importance of holes in initiating cracks, and of free surfaces in assisting their propagation by reflection at the specimen edge[3], has been confirmed.

(d) Using the fatigue-ultimate ratio $R_{0.0\ 10^6}$ for comparisons it is clear that CFC has a better zero-tension fatigue performance than thin aluminium alloy sheet. It has also been established that the values of this ratio are almost identical for the two carbon fibre reinforced epoxy materials which have been used to date in fatigue investigations.

(e) The effect of damage created by fatigue loads acting in one direction on the strength of the composite in other loading directions could not be investigated here. Nevertheless it is clear that effort is required to study this and combined loading effects.

(f) The photographs of broken specimens show that it may be difficult to distinguish between monotonic and fatigue failures simply by visual examination of some laminate constructions, particularly $90 \pm 45^\circ$ CFC.

(g) The work reported here confirms all the conclusions reported previously[3] which relate to the effect of fibre orientation on fatigue behaviour.

Table 1

MONOTONIC STRENGTH OF 8-PLY 0^{o} UNIDIRECTIONAL CFC. CODE 69 RESIN, TYPE 3 FIBRE

Specimen number	Tensile strength MPa
SA71/1	1134
SA71/6	1205
SA71/11	1346
SA71/16	1026
SA71/21	1078
Average strength	1157.8 MPa
Standard deviation	124 MPa
Coefficient of variation	10.7%

Table 2

MONOTONIC STRENGTH OF 6-PLY 0 ± 45^{o} MULTI-PLIED CFC. CODE 69 RESIN, TYPE 3 FIBRE

Specimen number	Tensile strength MPa
SA73/1	649.5
SA73/25	661.3
SA73/49	606.6
SA74/21	630.8
SA74/45	658.9
SA74/49	669.3
Average strength	646.1 MPa
Standard deviation	23.4 MPa
Coefficient of variation	3.6%

Table 3

MONOTONIC STRENGTH OF 6-PLY 0 ± 45^{o} MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE

Specimen number	Tensile strength MPa
SA73/2	401.4
SA73/26	417.4
SA73/50	339.4
SA74/22	465.3
SA74/46	427.4
SA74/50	420.0
Average strength	411.8 MPa
Standard deviation	41.4 MPa
Coefficient of variation	10.0%

Table 4

MONOTONIC STRENGTH OF 6-PLY 0 ± 45^{o} MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE PRECONDITIONING 3000 h AT 40^{o}C

Specimen number	Tensile strength MPa
SA73/4	403.8
SA73/28	403.3
SA73/52	459.7
SA74/24	427.0
SA74/48	416.3
SA74/52	392.5
Average strength	417.1 MPa
Standard deviation	24.0 MPa
Coefficient of variation	5.7%

Table 5

MONOTONIC STRENGTH OF 6-PLY 0 ± 45^{o} MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE PRECONDITIONING 3000 h AT 40^{o}C AND 95% RH

Specimen number	Tensile strength MPa
SA73/3	435.9
SA73/27	378.6
SA73/51	383.7
SA74/23	450.0
SA74/47	412.0
SA74/51	446.8
Average strength	417.8 MPa
Standard deviation	31.4 MPa
Coefficient of variation	7.5%

Table 6

MONOTONIC STRENGTH OF 6-PLY 90 ± 45^{o} MULTI-PLIED CFC. CODE 69 RESIN, TYPE 3 FIBRE

Specimen number	Tensile strength MPa
SA62/1	193.5
SA63/12	199.8
SA64/6	185.0
SA65/6	183.0
SA65/2	181.3
SA72/18	184.0
Average strength	187.8 MPa
Standard deviation	7.3 MPa
Coefficient of variation	3.9%

Table 7

MONOTONIC STRENGTH OF 6-PLY 90 ± 45^{o} MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE

Specimen number	Tensile strength MPa
SA62/2	192.0
SA63/13	179.0
SA64/7	180.6
SA65/7	183.9
SA65/3	183.8
SA72/19	168.7
Average strength	181.3 MPa
Standard deviation	7.6 MPa
Coefficient of variation	4.2%

Table 8

MONOTONIC STRENGTH OF 6-PLY 90 ± 45^{o} MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE PRECONDITIONING 3000 h AT 40°C

Specimen number	Tensile strength MPa
SA62/21	189.2
SA63/15	181.5
SA64/9	171.2
SA65/9	176.8
SA65/5	173.0
SA72/21	175.5
Average strength	177.9 MPa
Standard deviation	6.6 MPa
Coefficient of variation	3.7%

Table 9

MONOTONIC STRENGTH OF 6-PLY 90 ± 45^{o} MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE PRECONDITIONING 3000 h AT 40°C AND 95% RH

Specimen number	Tensile strength MPa
SA62/3	180.2
SA63/14	187.2
SA64/8	163.2
SA65/8	173.2
SA65/4	172.4
SA72/20	176.3
Average strength	175.4 MPa
Standard deviation	8.1 MPa
Coefficient of variation	4.6%

Table 10

ZERO-TENSION FATIGUE RESULTS FOR 8-PLY 0^{o} UNIDIRECTIONAL CFC. CODE 69 RESIN, TYPE 3 FIBRE. MONOTONIC TENSILE STRENGTH 1158 MPa. TESTING SPEED 20 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA71/2	350 ± 350	5071400*
SA71/7	350 ± 350	4980900*
SA71/10	375 ± 375	10000000*
SA71/20	" " "	8265000*
SA71/15	" " "	1733000
SA71/25	" " "	136400
SA71/3	400 ± 400	3235700*
SA61/13	" " "	5200
SA71/22	" " "	2900
SA71/8	" " "	2500
SA71/24	425 ± 425	25400
SA71/14	" " "	19300
SA71/5	" " "	3700
SA71/19	" " "	1300
SA71/23	450 ± 450	2850400
SA71/18	" " "	16200
SA71/9	" " "	8500
SA71/4	" " "	3900
SA71/12	500 ± 500	**
SA71/17	500 ± 500	**

* Run-out

** Run-up failure

Table 11

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 0 ± 45° MULTI-PLIED CFC. CODE 69 RESIN, TYPE 3 FIBRE. MONOTONIC TENSILE STRENGTH 646 MPa. TESTING SPEED 20 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA73/9	200 ± 200	2959300
SA74/5	" " "	2570800
SA74/29	" " "	2124000
SA73/23	" " "	400500
SA73/17	215 ± 215	895300
SA74/37	" " "	93400
SA73/41	" " "	6700
SA74/13	" " "	6200
SA73/5*	225 ± 225	342560
SA73/29	" " "	29100
SA74/1	" " "	9700
SA74/25	" " "	5100
SA74/33	232.5 ± 232.5	403900
SA74/9	" " "	314800
SA73/37	" " "	4600
SA73/13	" " "	1090

* Tested at 10 Hz

Table 12

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 0 ± 45° MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. MONOTONIC TENSILE STRENGTH 412 MPa. TESTING SPEED 20 Hz.

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA73/6	150 ± 150	7105300*
SA73/10	160 ± 160	3414500*
SA74/18	170 ± 170	8837300*
SA74/42	" " "	4994500*
SA73/22	" " "	3955500
SA73/46	" " "	1236600
SA74/6	175 ± 175	11113300
SA73/34	175 ± 175	5515000
SA74/14	180 ± 180	2012300
SA74/26	" " "	540000
SA73/42	" " "	**
SA73/18	" " "	**
SA74/38	" " "	**
SA73/14	190 ± 190	**

* Run-out

** Specimen failed on first loading

031

Table 13

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 0 ± 45^{o} MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. PRECONDITIONING 3000 h AT 40^{o}C. MONOTONIC TENSILE STRENGTH 417 MPa. TESTING SPEED 20 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA73/16	180 ± 180	5128300*
SA74/36	" " "	5028800*
SA74/12	" " "	1632400
SA73/40	" " "	406700
SA74/4	190 ± 190	3708000
SA73/8	" " "	949100
SA74/28	" " "	772400
SA73/32	" " "	660200
SA74/8	195 ± 195	233500
SA73/12	" " "	222700
SA74/32	" " "	Failed on run-up
SA73/36	" " "	Failed on run-up

* Run-out

Table 14

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 0 ± 45^{o} MULTI-PLIED CFC CONTAINING A 2mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. PRECONDITIONING 3000 h AT 40^{o}C AND 95% RH. MONOTONIC TENSILE STRENGTH 418 MPa. TESTING SPEED 20 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA74/3	180 ± 180	4910000*
SA74/27	" " "	4785400*
SA73/7	" " "	2644100
SA73/31	" " "	2169500
SA73/35	190 ± 190	1951000
SA74/7	" " "	1234500
SA74/31	" " "	1014400
SA73/11	" " "	294800
SA73/15	195 ± 195	1577900
SA74/11	" " "	810100
SA74/35	" " "	**
SA73/39	" " "	**

* Run-out

** Specimen failed on first loading

Table 15

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 90 ± 45° MULTI-PLIED CFC. CODE 69 RESIN, TYPE 3 FIBRE. MONOTONIC TENSILE STRENGTH 188 MPa. TESTING SPEED 10 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA62/4	40.5 ± 40.5	5732700*
SA64/3	45 ± 45	4383400
SA72/15	" " "	3531800
SA63/9	" " "	1719000
SA64/22	52.5 ± 52.5	290800
SA62/17	" " "	290200
SA72/11	" " "	263900
SA63/5	" " "	176700
SA62/9	60 ± 60	131400
SA63/20	" " "	53200
SA64/14	" " "	43300
SA72/3	" " "	29800
SA64/10	70 ± 70	13520
SA72/22	" " "	9410
SA62/5	" " "	8400
SA63/16	" " "	6500
SA72/7	75 ± 75	5120
SA63/1	" " "	3370
SA64/18	" " "	2960
SA62/13	" " "	2850

* Run-out

Table 16

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 90 ± 45^{o} MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. MONOTONIC TENSILE STRENGTH 181 MPa. TESTING SPEED 10 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA63/10	42.5 ± 42.5	4070400
SA64/4	" " "	2931000
SA62/22	" " "	2917600
SA63/6	50 ± 50	514000
SA64/23	" " "	398800
SA62/18	" " "	289600
SA72/12	" " "	98700
SA62/14	57.5 ± 57.5	63800
SA63/2	" " "	47700
SA64/19	" " "	26000
SA72/8	" " "	19800
SA62/10	65 ± 65	13530
SA63/21	" " "	10550
SA72/4	" " "	6990
SA64/15	" " "	6410
SA62/6	72.5 ± 72.5	6320
SA63/17	" " "	2080
SA72/23	" " "	1710
SA64/11	" " "	1660

Table 17

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 90 ± 45° MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. PRECONDITIONING 3000 h AT 40°C. MONOTONIC TENSILE STRENGTH 178 MPa. TESTING SPEED 10 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA62/16	42.5 ± 42.5	3420000*
SA63/4	" " "	3410000
SA64/21	" " "	805000
SA72/10	" " "	455000
SA64/2	50 ± 50	348000
SA63/8	" " "	144200
SA62/20	" " "	109500
SA72/14	" " "	56400
SA63/23	57.5 ± 57.5	33100
SA62/12	" " "	31000
SA72/6	" " "	21400
SA64/17	" " "	10200
SA63/19	65 ± 65	10830
SA64/13	" " "	9230
SA62/8	" " "	8200
SA72/2	" " "	7650
SA64/5	72.5 ± 72.5	1750
SA65/10	" " "	1440
SA72/16	" " "	1020
SA62/24	" " "	980

* Run-out

Table 18

ZERO-TENSION FATIGUE RESULTS FOR 6-PLY 90 ± 45° MULTI-PLIED CFC CONTAINING A 4mm HOLE. CODE 69 RESIN, TYPE 3 FIBRE. PRECONDITIONING 3000 h at 40°C AND 95% RH. MONOTONIC TENSILE STRENGTH 175 MPa. TESTING SPEED 10 Hz

Specimen number	Fatigue stresses MPa	Number of cycles to failure
SA65/11	42.5 ± 42.5	3459400
SA72/17	" " "	2486500
SA62/23	" " "	2449700
SA63/11	" " "	1417000
SA62/19	50 ± 50	565900
SA64/1	" " "	444200
SA63/7	" " "	264700
SA72/13	" " "	109200
SA72/5	57.5 ± 57.5	68500
SA62/11	" " "	63800
SA63/22	" " "	63800
SA64/16	" " "	56200
SA72/1	65 ± 65	20700
SA62/7	" " "	20600
SA64/12	" " "	19300
SA63/18	" " "	14900
SA63/3	72.5 ± 72.5	7450
SA64/20	" " "	4890
SA62/15	" " "	2660
SA72/9	" " "	2020

031

REFERENCES

No.	Author	Title, etc.
1	B. Harris	Fatigue and accumulation of damage in reinforced plastics. *Composites*, 8, 4, p 214 (1977)
2	J.B. Sturgeon	Fatigue of multi-directional carbon fibre reinforced plastics. *Composites*, 8, 4, p 221 (1977)
3	J.B. Sturgeon K.S. McLaughlin B.B. Moore	The fatigue properties of 0°, $\pm 45^{\circ}$, $0 \pm 45^{\circ}$ and $90 \pm 45^{\circ}$ carbon fibre reinforced plastics. RAE Technical Report 76153 (1976)
4	J.B. Sturgeon	Fatigue testing of carbon fibre reinforced plastics. RAE Technical Report 75135 (1975)
5	F. Clifton	Strength variability in structural materials. RAE Technical Report 69015 (1969)
6	J.B. Sturgeon	Unpublished MOD work.
7	J.B. Sturgeon	Creep, repeated loading, fatigue and crack growth in $\pm 45^{\circ}$ oriented carbon fibre reinforced plastics. RAE Technical Report 76105 (1976)
8	L.G. Bevan J.B. Sturgeon	Fatigue limits in CFRP. Paper 32, 2nd International Conference on carbon fibres: their place in modern technology, the Plastics Institute, London (1974)
9	Sarah M. Bishop	Deformation near notches in angleplied carbon fibre composites. RAE Technical Report 77093 (1977)
10	R.T. Potter	On the mechanism of tensile fracture in notched fibre reinforced plastics. RAE Technical Report 77023 (1977)
11	R.E. Davies G.E. Nordmark J.D. Walsh	Design mechanical properties, fracture toughness, fatigue properties, exfoliation and stress corrosion resistance of 7050 sheet, plate hand forgings, die forgings and extensions. Alcoa Laboratories report to the Naval Air Systems Command, Washington DC. Report T76 121 (1974)

REFERENCES (concluded)

No.	Author	Title, etc
12	M.S. Binning	Direct stress fatigue tests on DTD 5070A, BSL 73 and Alclad 2024-T81 sheets. RAE Technical Report 70221 (1970)

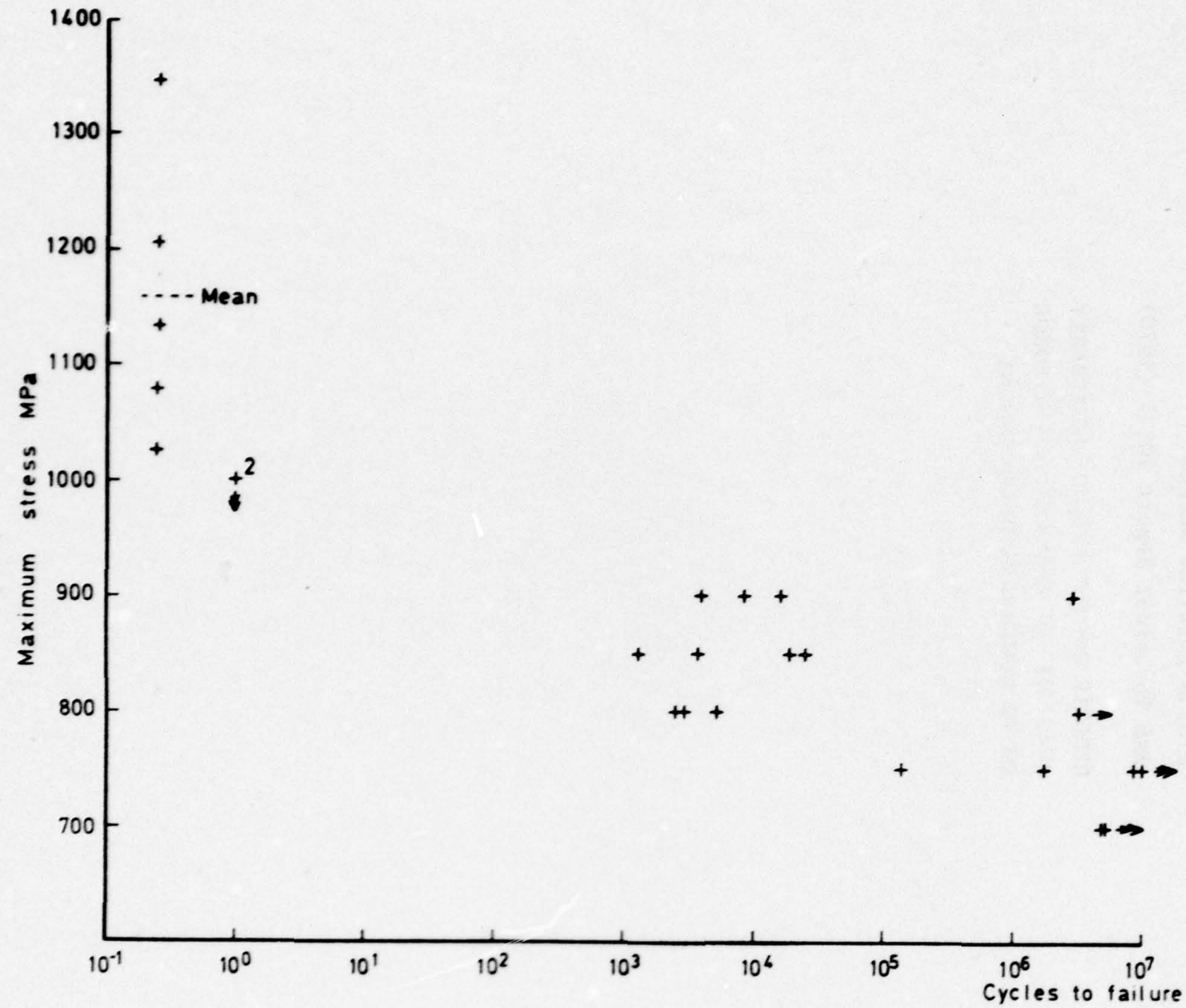


Fig 1 S-N diagram of unidirectional 0° CFC. Resin Code 69, fibre type 3 treated

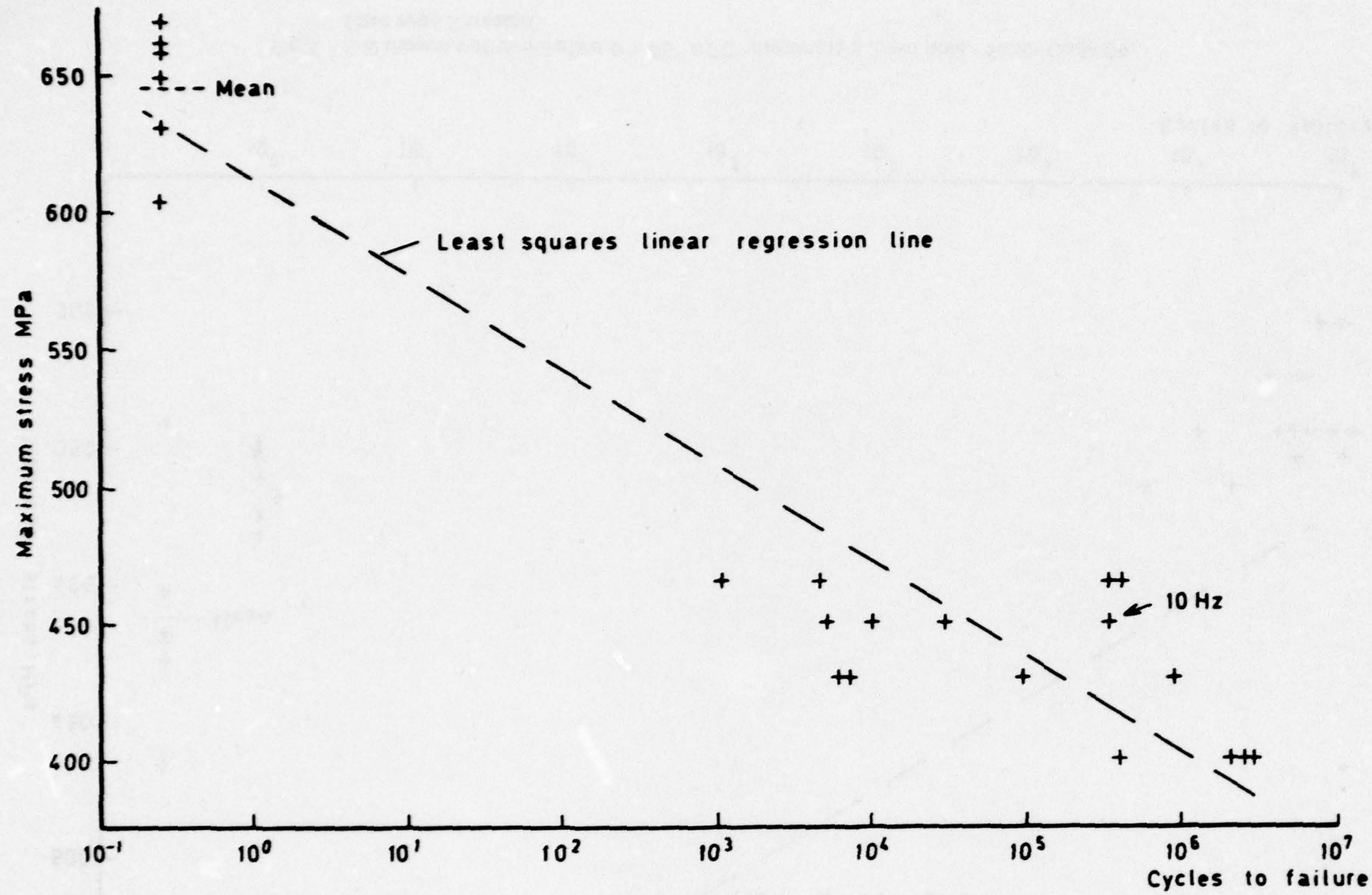


Fig 2 S-N diagram of multi-plied 0 ± 45° CFC. Resin Code 69, fibre type 3 treated

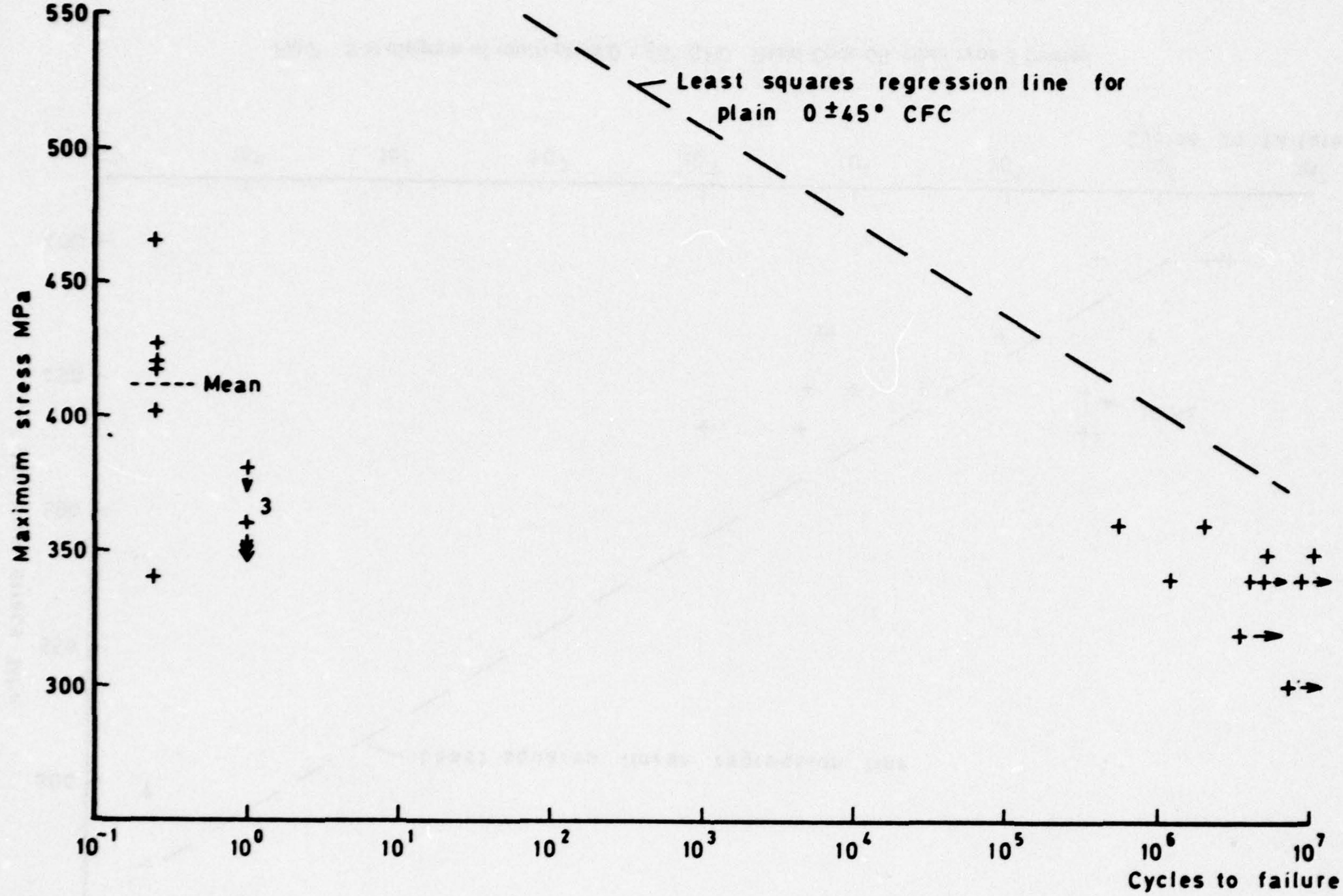


Fig 3 S-N diagram of multi-plied 0 ± 45° CFC containing a 2mm hole. Resin Code 69, fibre type 3 treated

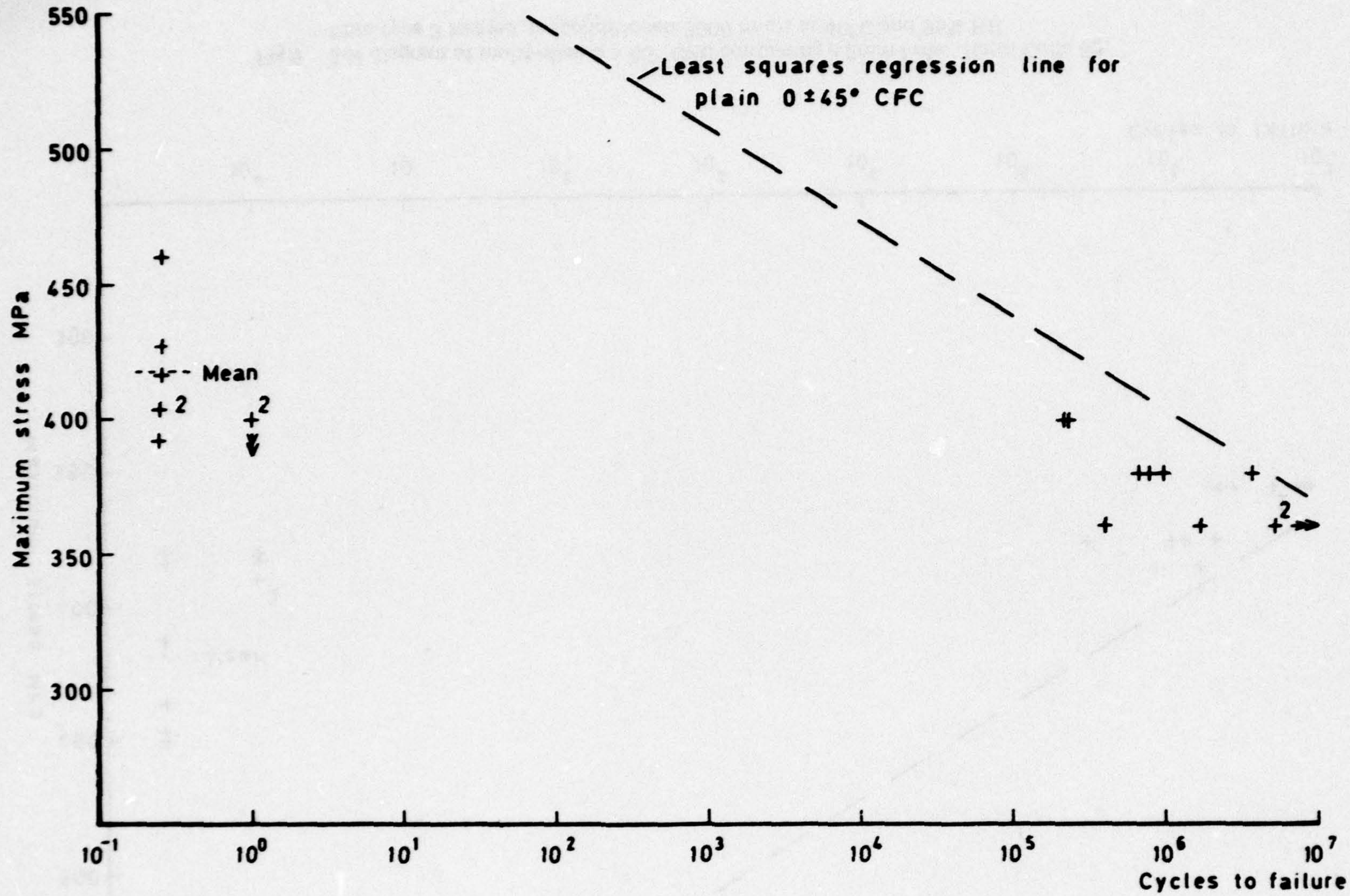


Fig 4 S-N diagram of multi-plied 0 ± 45° CFC containing a 2mm hole. Resin Code 69, fibre type 3 treated, preaged 3000 hours at 40°C

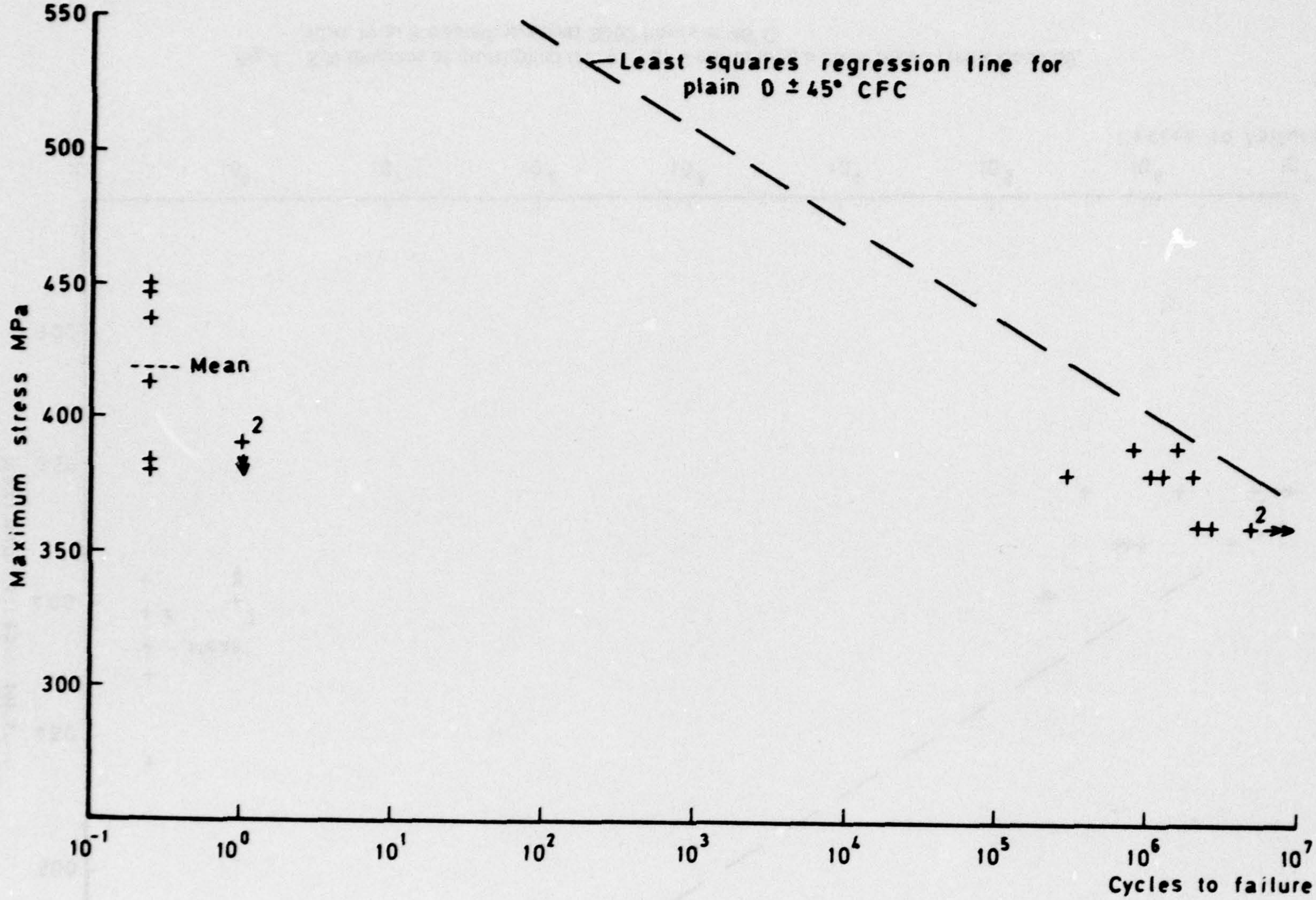


Fig 5 S-N diagram of multi-plied 0 ± 45° CFC containing a 2mm hole. Resin Code 69, fibre type 3 treated, preconditioned 3000 hours at 40°C and 95% RH

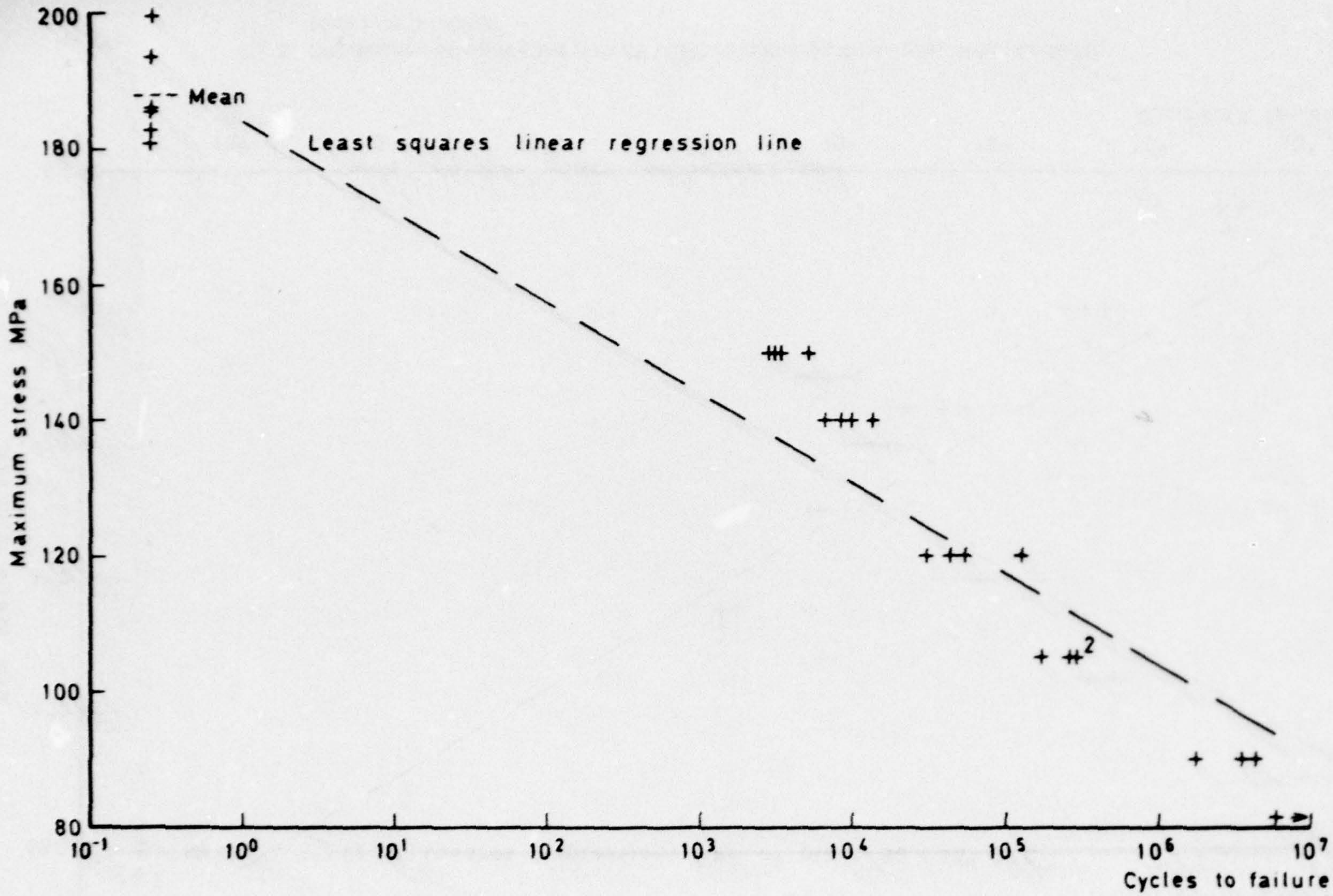


Fig 6 S-N diagram of multi-plied 90 ± 45° CFC. Resin Code 69, fibre type 3 treated

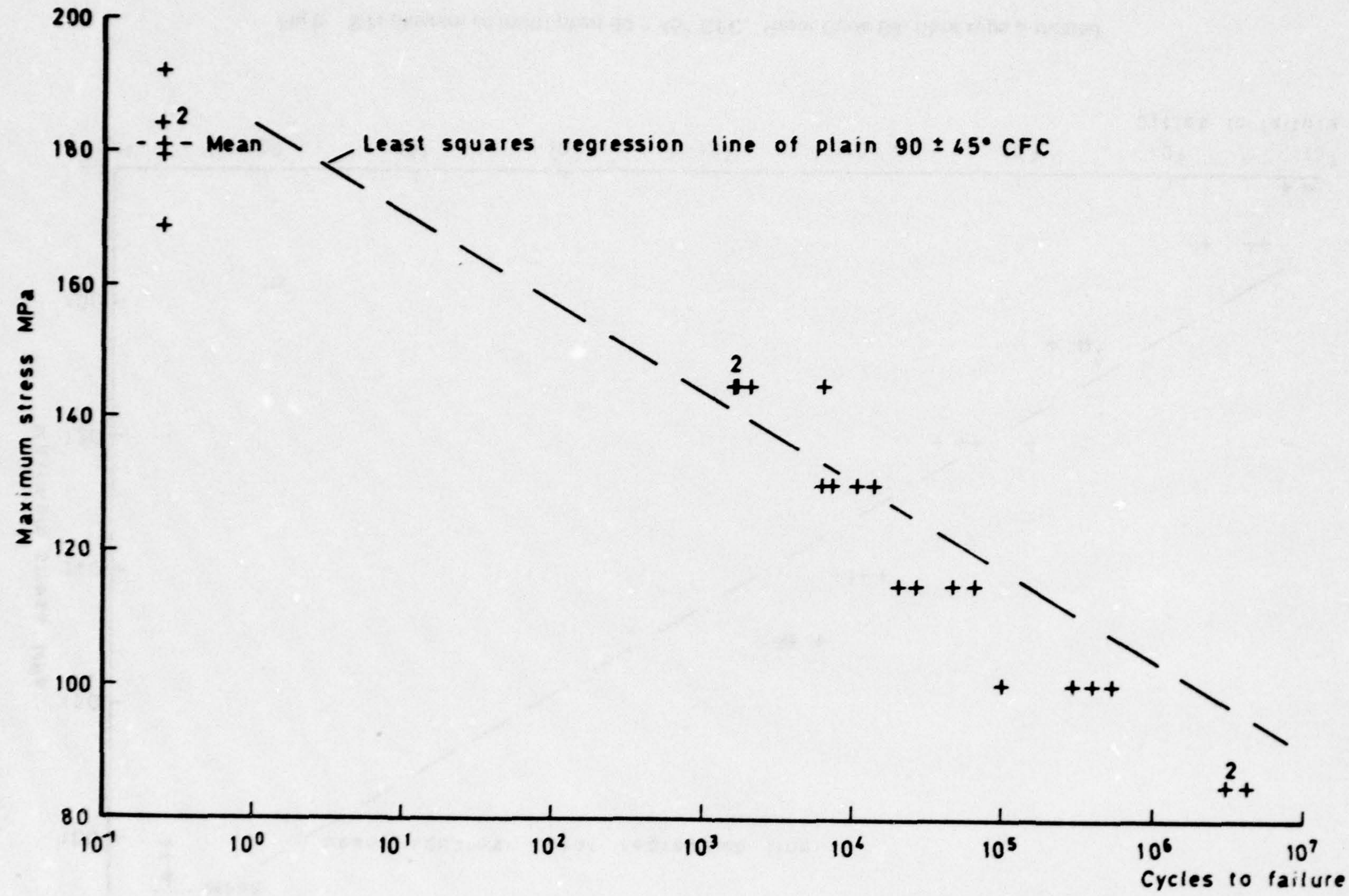


Fig 7 S-N diagram of multi-plied 90 ± 45° CFC containing a 4mm hole. Resin Code 69, fibre type 3 treated

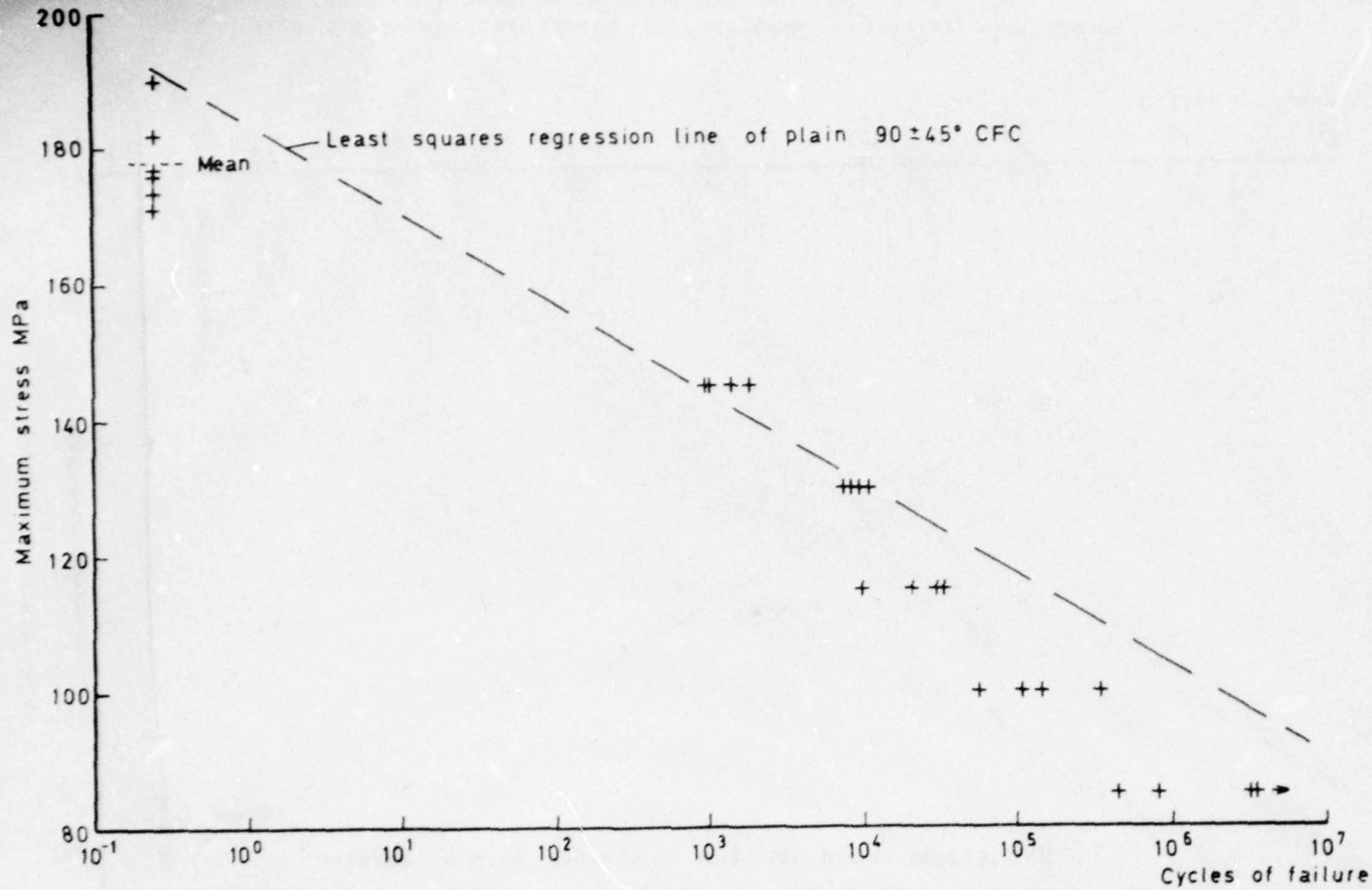


Fig 8 S-N diagram of multi-plied 90 ± 45° CFC containing a 4mm hole. Resin Code 69, fibre type 3 treated, preaged 3000 hours at 40°C

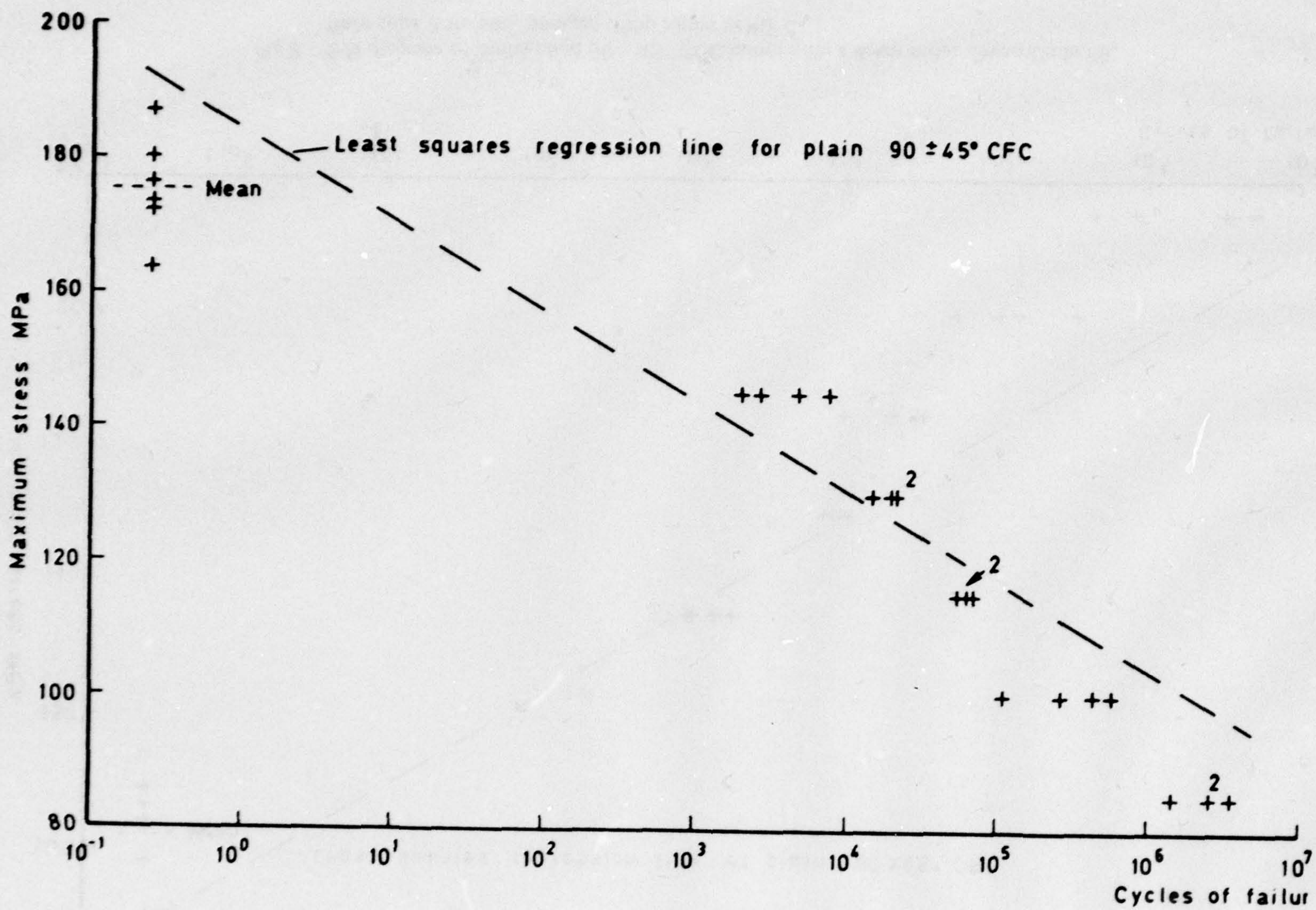


Fig 9 S-N diagram of multi-plied 90 ± 45° CFC containing a 4mm hole. Resin Code 69, fibre type 3 treated, preconditioned 3000 hours at 40°C and 95% RH

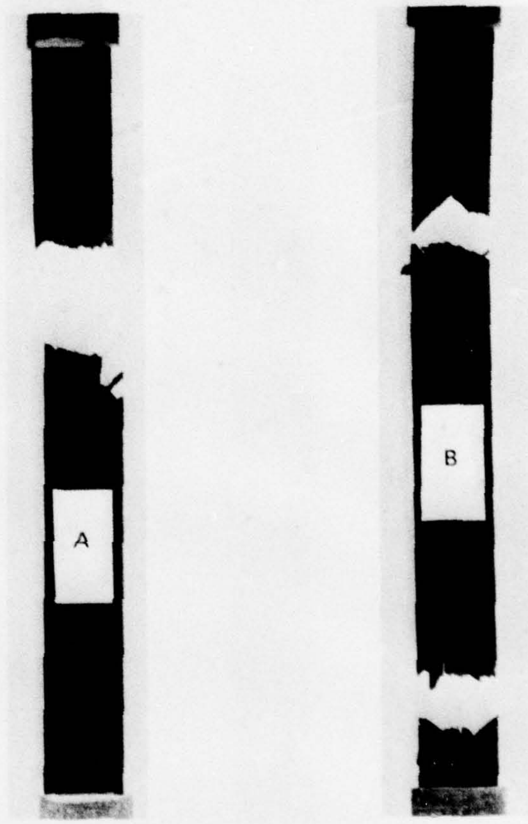


Fig 10 Monotonic failures of multi-plied 0 ± 45° CFC

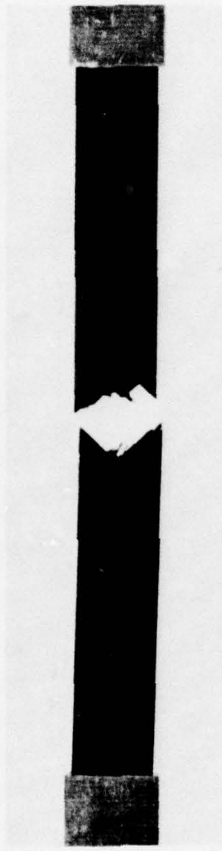


Fig 11 Monotonic failure of multi-plied 0 ± 45° CFC containing a 2mm diameter hole

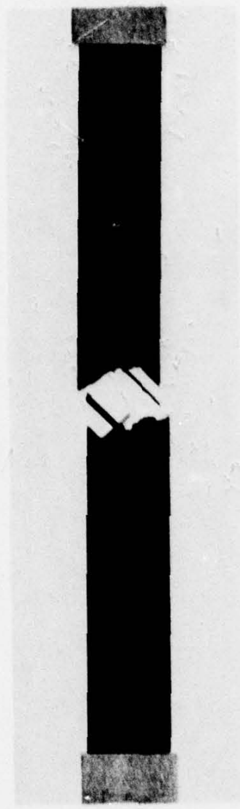


Fig 12 Monotonic failure of multi-plied 0 ± 45° CFC containing a 2mm diameter hole. Tested after preageing for 3000 hours at 40°C

Fig 13

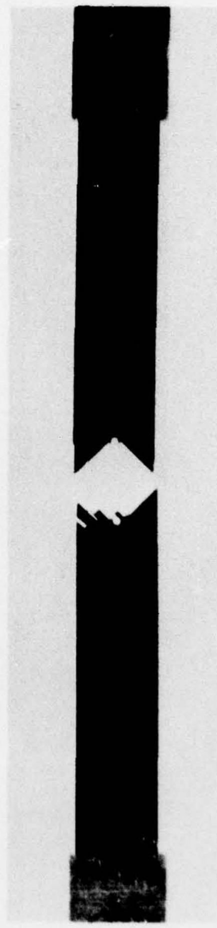


Fig 13 Monotonic failure of multi-plied at $0 \pm 45°$ CFC containing a 2mm diameter hole. Tested after preconditioning for 3000 hours at 40°C and 95% RH

TR 78031 C14771

Fig 14 Fatigue failures of multi-plied 0 ± 45° CFC. The endurances to failure were; specimen (A) 2959300, (B) 342560, (C) 93400, (D) 21100 cycles

Fig 15

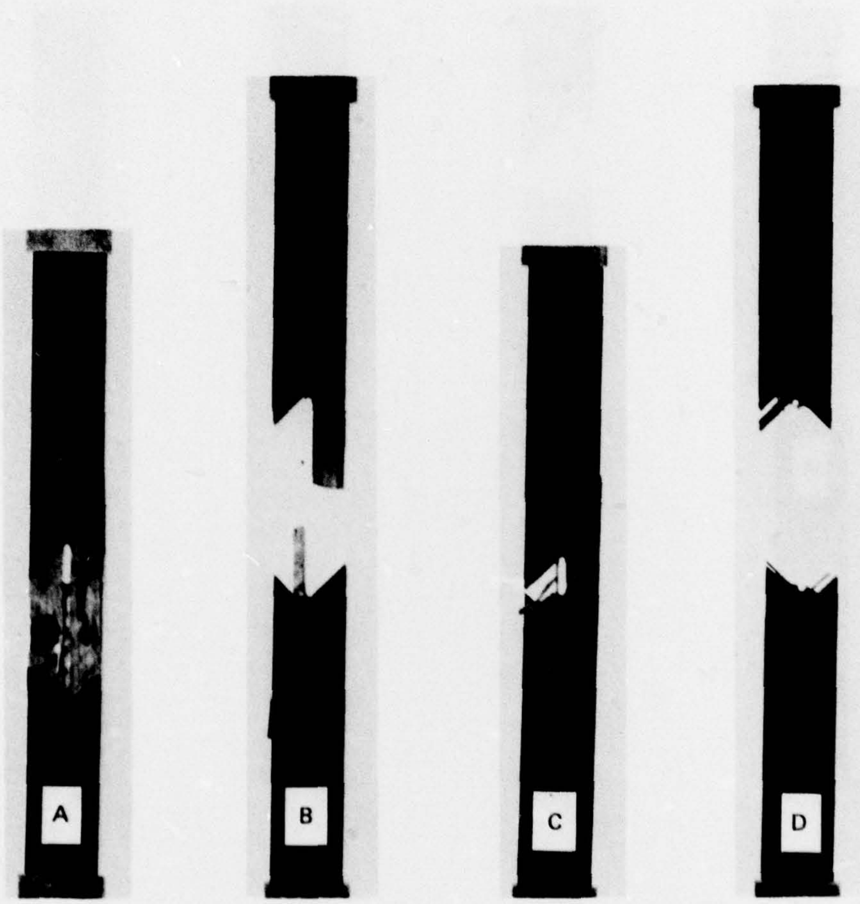


Fig 15 Fatigue failures of multi-directional 0 ± 45° CFC containing a 2mm diameter hole. The endurances to failure were; specimen (A) 11113300, (B) 3955500, (C) 2012300 cycles, (D) failed on run-up to full load

TR 78031 C14773

Fig 16 Fatigue failures of multi-directional 0 ± 45° CFC containing a 2mm diameter hole. Specimens were preaged for 3000 hours at 40°C and *their endurances to failure were*; specimen (A) 1632400, (B) 949100, (C) 233500 cycles

Fig 17 Fatigue failures of multi-directional 0 ± 45° CFC containing a 2mm diameter hole. Specimens were preconditioned for 3000 hours at 40°C and 95% RH and their endurances to failure were; specimen (A) 2644100, (B) 1234500, (C) 810100 cycles, (D) failed on run-up to full load

TR 78031 C14775

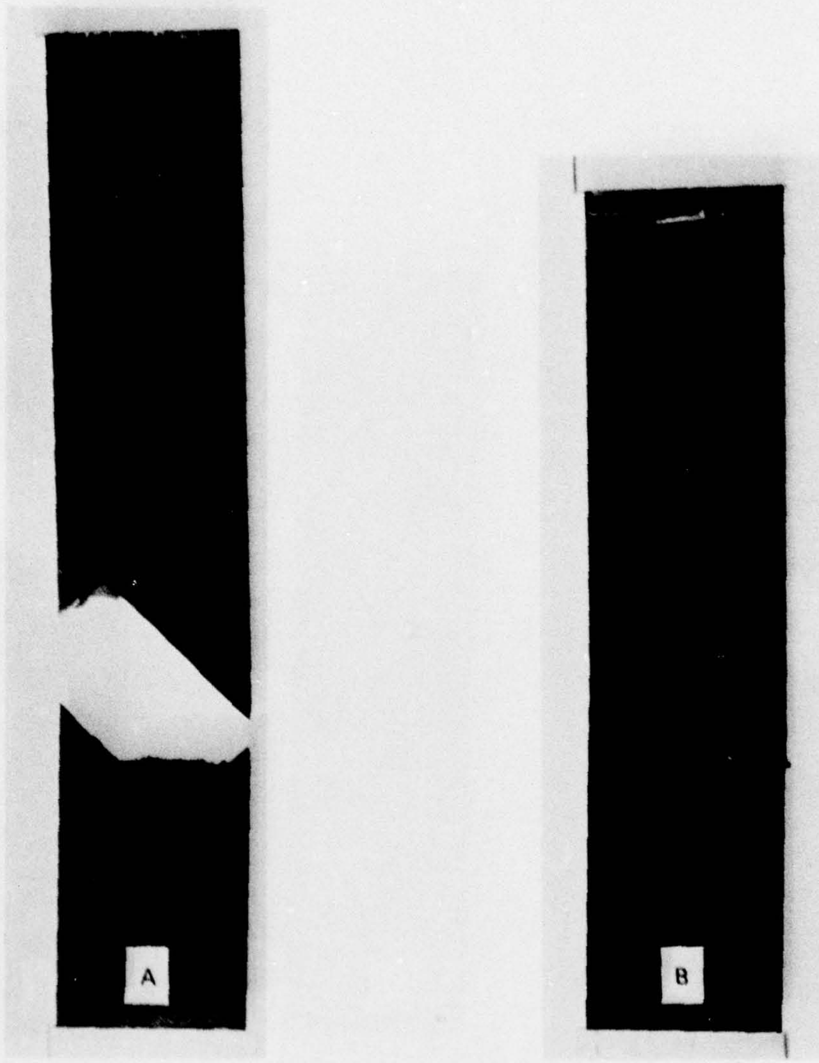


Fig 18 Monotonic failures of multi-plied 90 ± 45° CFC

Fig 19

Fig 19 Monotonic failures of multi-plied 90 ± 45° CFC containing a 4mm diameter hole

TR 78031 C14777

Fig 20 Monotonic failures of multi-plied 90 ± 45° CFC containing a 4mm diameter hole. Tested after preageing for 3000 hours at 40°C

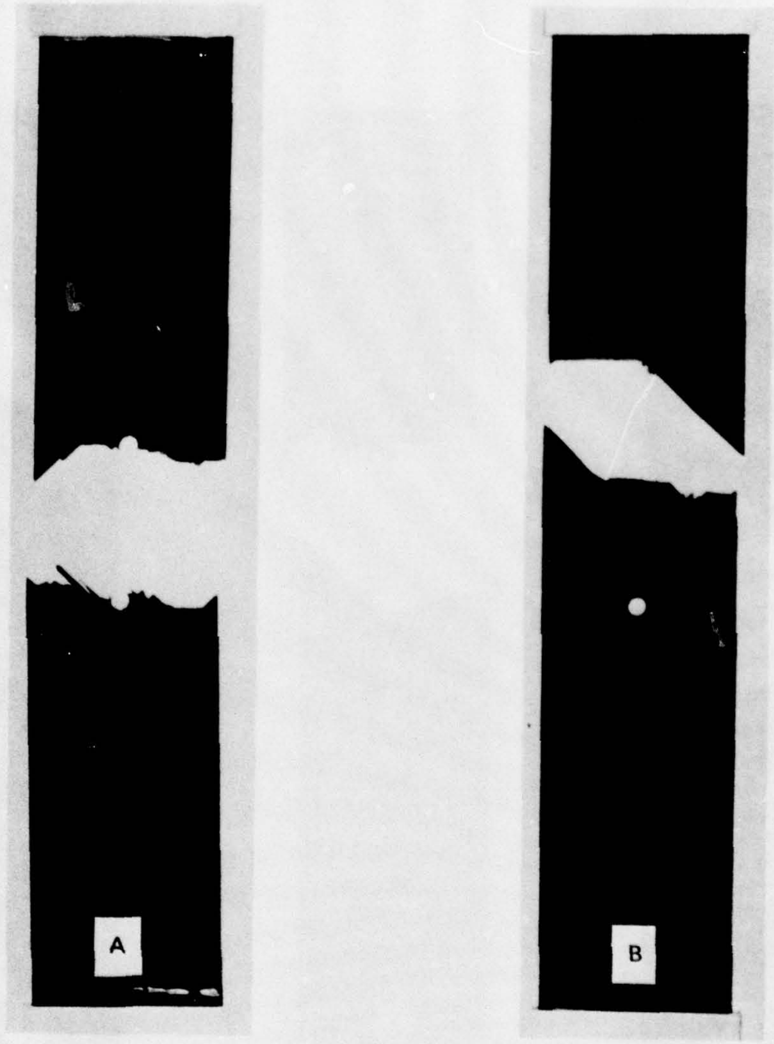


Fig 21 Monotonic failures of multi-plied 90 ± 45° CFC containing a 4mm diameter hole. Tested after preconditioning for 3000 hours at 40°C and 95% RH

TR 78031 C14779

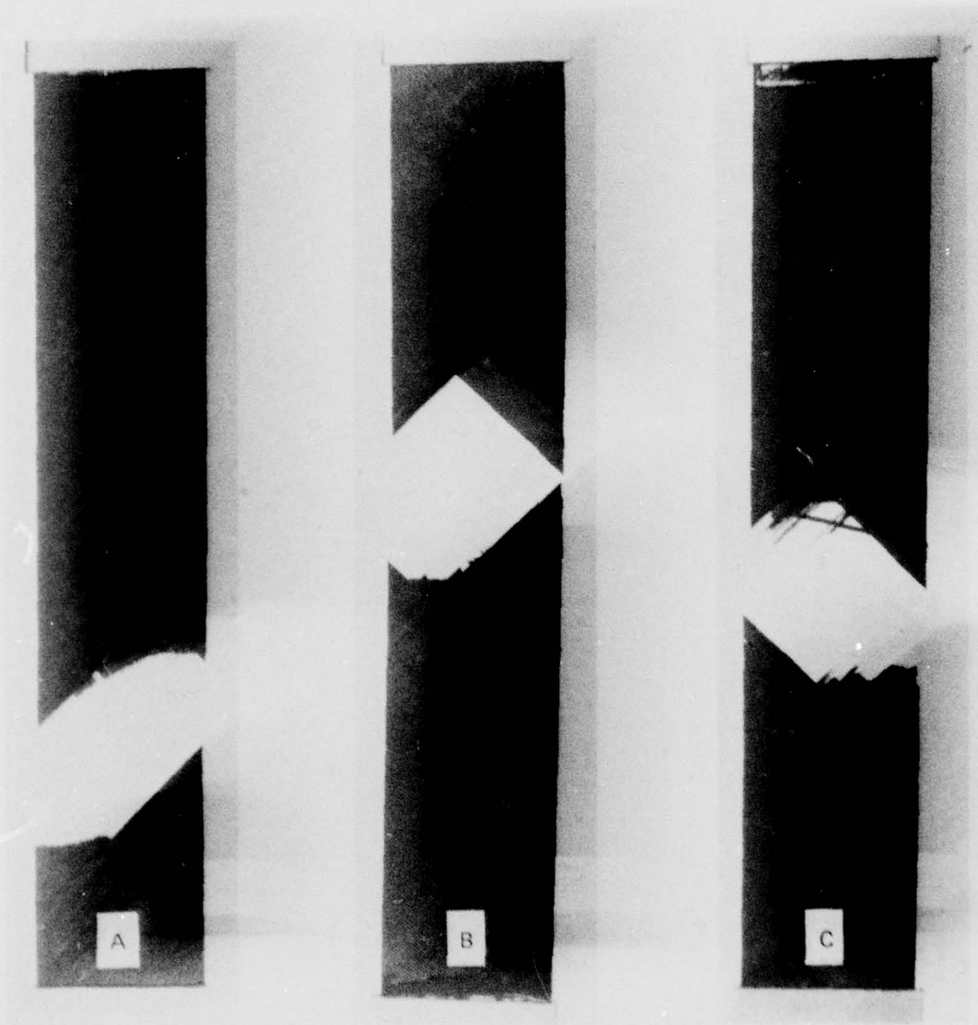


Fig 22 Fatigue failures of multi-plied 90 ± 45° CFC. The endurances to failure were; specimen (A) 1719000, (B) 8400, (C) 5120 cycles

Fig 23

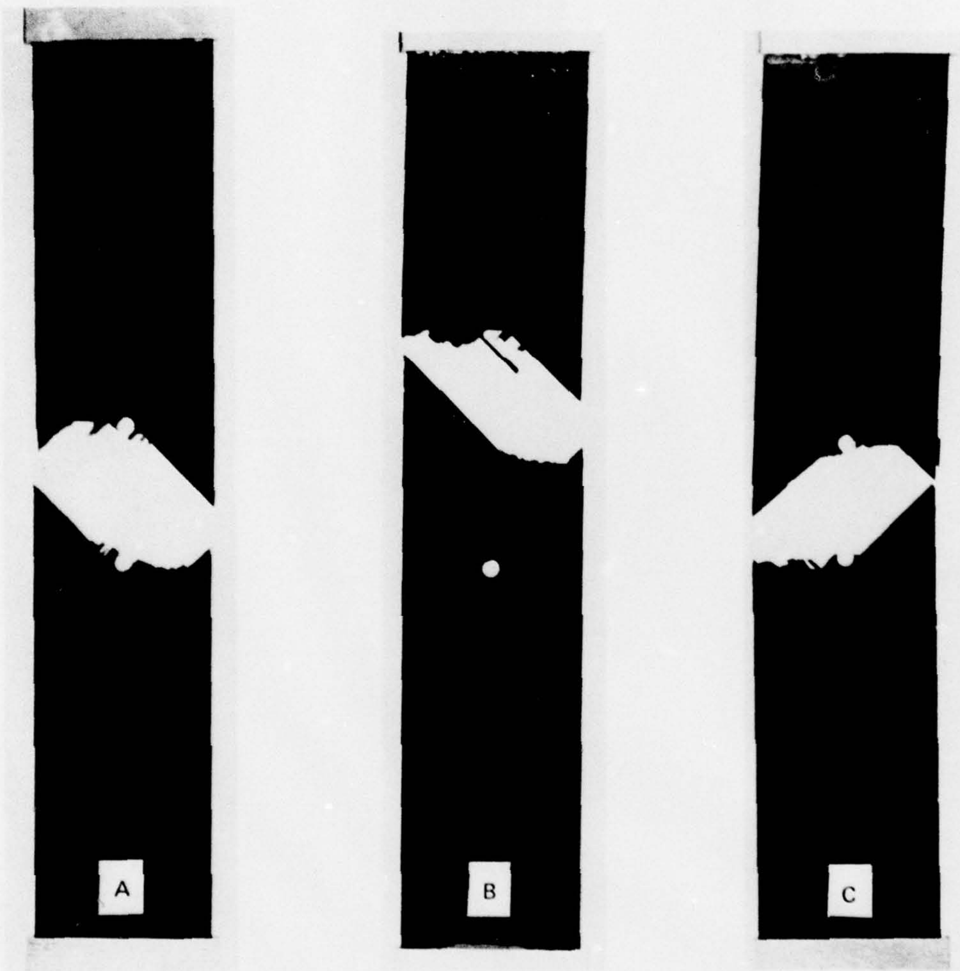


Fig 23 Fatigue failures of multi-directional 90 ± 45° CFC containing a 4mm diameter hole. The endurances to failure were; specimen (A) 4070400, (B) 289600, (C) 6990 cycles

TR 78031 C14781

Fig 24 Fatigue failures of multi-plied 90 ± 45° CFC containing a 4mm diameter hole. Specimens were preaged for 3000 hours at 40°C and their endurances to failure were; specimen (A) 455000, (B) 348000, (C) 33100, (D) 1440 cycles

TR 78031 C14782

Fig 25

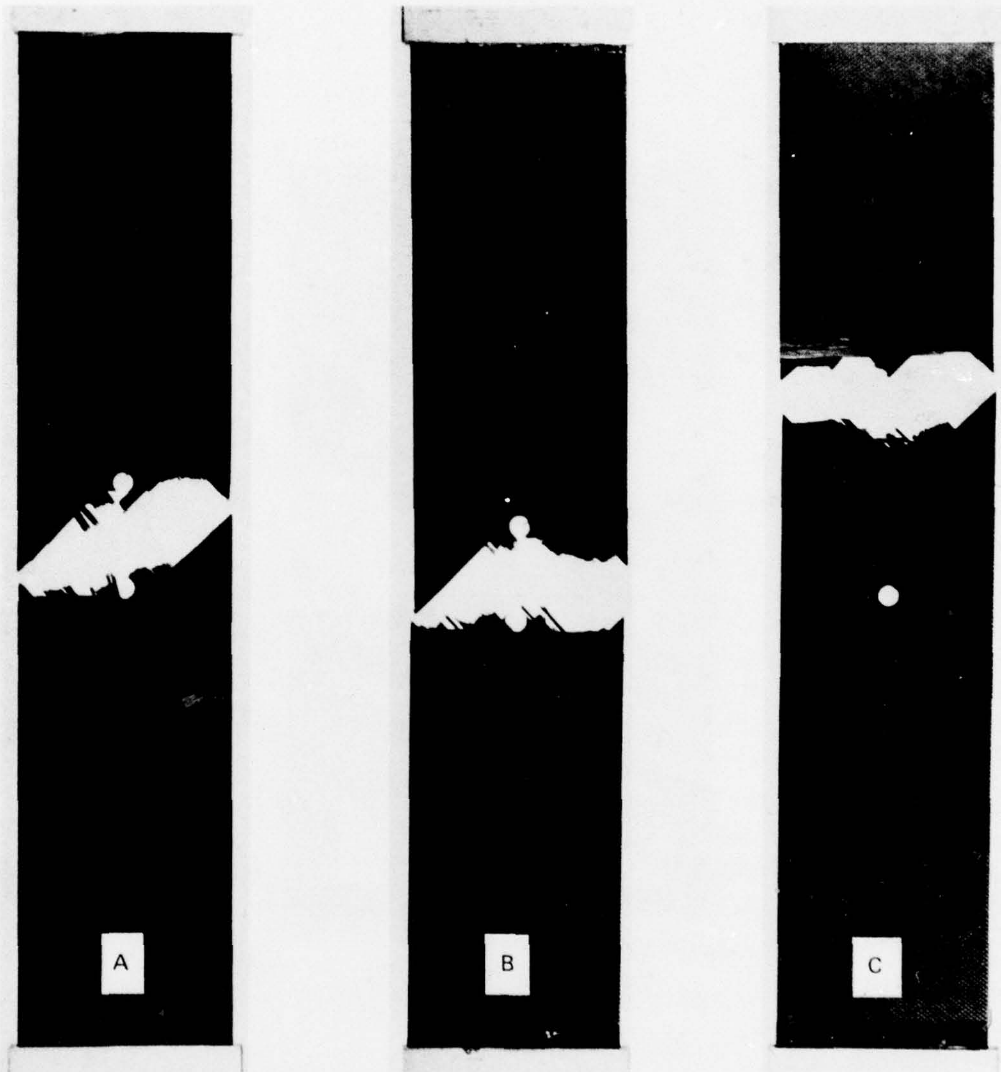


Fig 25 Fatigue failures of multi-plied 90 ± 45° CFC containing a 4mm diameter hole. Specimens were preconditioned for 3000 hours at 40°C and 95% RH and their endurances to failure were; specimen (A) 2449700, (B) 20600, (C) 4890 cycles

TR 78031 C14783